Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

(2)

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a	3. DISTRIBUTION/AVAILABILITY OF REPORT Unlimited
2b AD-A250 209	
4.	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 92 0388

6a. NAME OF PERFORMING ORGANIZATION	6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
Princeton University		AF Office of Scientific Research

6c. ADDRESS (City, State, and ZIP Code)	7b. ADDRESS (City, State, and ZIP Code)
Office of Research & Project Administration Princeton, NJ 08544-0636	Bldg. 410 Bolling AFB, DC 20332-6448

8a. NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
AFOSR/PKD; AFOSR/NA	NA	Grant AFOSR 89-0033

8c. ADDRESS (City, State, and ZIP Code)

Bldg. 410
Bolling AFB, DC 20332-6448

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
61102F	2307	A1	

11. TITLE (Include Security Classification)
THE STRUCTURE AND CONTROL OF THREE-DIMENSIONAL SHOCK WAVE TURBULENT BOUNDARY LAYER INTERACTIONS - Unclassified

12. PERSONAL AUTHOR(S)
Seymour M. Bogdonoff and Alexander J. Smits

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 10/1/88 TO 8/31/91	March 20, 1992	30

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Turbulent Boundary Layers, Crossing Shocks, Reflected Shock Information

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

See Introduction

DTIC ELECTE MAY 19 1992 S A D

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION	
☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	U	
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL
Dr. Leonidas Sakell	202-767-4987	NA

DD Form 1473, JUN 86 Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

INTRODUCTION

The three year period covered in the subject report was a considerable shift from the previous years of work on shock wave turbulent boundary layer interactions. The earlier work concentrated on simple "building block" experiments and a search for fundamental understanding of the flow phenomena. In the subject research, most of the work on fundamentals for the simple configurations was stopped. The main emphasis for the first two years of the current program was on complex configurations and the final year was a "close-out" program on a new approach. The work on complex configurations was limited to two geometries which used the much studied single sharp fin interaction, Fig. 1, as the initial conditions. This shift in emphasis had two main purposes: 1) to test the ability to use the building block experiments in more complex interactions required for applications and 2) to provide a more critical test of computation which, although giving the general characteristics for the building block experiments, did not give highly quantitative results.

The primary activities for the first two years will be discussed in three major groupings: (1) and (2) Discussions of the two complex configurations, and (3) a description of the boundary layer conditions which are critical to the definition of the experiment and the check by computational fluid dynamics. None of these three efforts are totally complete, but they provide a unique set of results which sets some perspective on the use of building block experiments and the ability of computation to predict these complex flows. The specific test configurations were chosen to provide the best definition of the test geometry and flow field, both to clarify the interactions and to simplify the requirements for the computation. Concentration was placed on complex interactions which are a link to direct

applications for external aerodynamics, and particularly, for inlets and inlet-airframe integration. The work undertaken during the third year of the subject contract is covered separately in the latter part of the report.

The work covered in the first two years is organized, in the following sections, as follows:

1) A brief review of the three major efforts carried out, with the major contributions and status of each program delineated.

2) A brief outline of the deferred studies, and the status of these studies.

3) Some comments on future possibilities.

4) The reports and publications generated during and since the grant years.

Although the major support for this work came under AFOSR Grant 89-0033, monitored by Dr. Len Sakell, the level of support was inadequate to complete the program. The OSR funds for the first two years were supplemented by funds from NASA-Ames and Lewis Laboratories through NASA Grant NAG3-926, monitored by Dr. Bernard Anderson and Dr. A. R. Porro, and NASA Grant NAG2-718, monitored by Dr. Joseph Marvin.

<u>Staff Involvement (first two years)</u>:

Seymour M. Bogdonoff, Principal Investigator

Kamal Poddar, Research Staff

William Stokes, Technical Specialist (wind tunnel)

Richard Gilbert, Technical Specialist (computer)

Andrew Ketchum, Graduate Student

Steve Toby, Graduate Student

Wolfgang Konrad, Graduate Student

Staff Involvement (third year):

Alexander J. Smits, Professor

Wolfgang Konrad, Graduate Student

The third year was funded under AFOSR Grant 89-0033, and the nature of that work, and the results obtained, are discussed in Section 5.

1. BRIEF REVIEW OF THE THREE MAJOR EFFORTS

The major activity ~~for the first two years~~ was directed at the two complex interactions - crossing shocks and reflected shock interactions with a turbulent boundary layer, with a secondary effort placed on the study of the turbulent boundary layer on the flat plate to define, in detail, the initial conditions for the above two tests.

(2) (3.)

a) The Cross Shock Configuration, Fig. 2

The initial highly detailed wall static pressure distributions and some very preliminary nonsteady static pressure and heat transfer were completed during the previous year and first reported in Ref. 1. High resolution wall static pressure distributions and nonsteady measurements indicated new phenomena for this interaction. The second phase of the study, completed during the following year, concentrated on obtaining some general idea of nonsteadiness by using high frequency wall static pressure measurements and reported in Ref. 2. These results provided a good framework for the third phase of this work which concentrated on the effect of fin length on the generated flowfield (as indicated by wall static pressures).

The first pressure distribution results were provided to Prof. Doyle Knight and Dr. Mike Horstman, and the first attempts to compute this flowfield are presented in Ref. 3. Although the results for computations and experiments for simple fin configurations showed general agreement, with significant differences in details, the comparison for the complex cross shock interaction was much less satisfactory. The distributions of static pressure on the wall, both longitudinal and transverse, show significant differences. This throws considerable doubt on the ability of the computations to provide the general flowfield models which were shown to be effective for the simple configurations. The second data set, for longer fins, has

been completed, with a wall static pressure distribution resolution of about half the original work. The initial analysis of these results was presented at the AIAA Reno Meeting, 1992, Ref. 4.

Results and Conclusions

1) The program has provided, at a Mach number of about 3, very detailed wall static test pressure distributions for a range of configurations involving crossing shocks and their interaction with turbulent boundary layers. The entrance conditions are a well defined turbulent boundary layer, and the span to boundary layer aspect ratio is about 30 while the height to boundary layer thickness aspect ratio is about 20. For symmetrical configurations, the data set provides results from 7 to 11^{o} shock deflections for the 9" fins, and 4 to 11^{o} for the 11" fins. For the assymetric configuration with the 9" fins, 7 to 13^{o} was the range covered. The static pressure distribution resolution was less than the original boundary layer thickness for the 9" fins, with about twice that resolution for the 11" fins. The detailed pressure distributions covered the full interaction on the floor, past the exit for the 9" fins and close to the exit for the 11" fins. The wide range of geometries, as shown in Fig. 3, includes the interaction with no wall reflections, the inviscid shock just touching the trailing edge of the fins, and with full reflections from the fin walls. Some examples of the detailed wall pressure distributions are shown in Figs. 4 and 5.

2) For the configuration studied, the extent of the initial single fin interactions has been delineated. Once the structures from each fin start to interact, there is a generally common pressure distribution structure, but there are significant differences in the development downstream as the fin angle (shock wave strength) is varied. The flow downstream clearly has some complicated structure. There is no uniform region at the theoretical inviscid shock pressure ratio, and the inviscid

shock wave analysis would seem to be a very poor approxiamtion of this flow. The key unanswered questions are primarily associated with the structure of the flow after the initial interactions take place.

3) The only computations which have been made for this specific set of experiments is that of Ref. 3. The comparison of their results (from Ref. 3) for the 11^{o} interaction is shown in Figs. 6 and 7. As noted in that report, and clear from the examination of the two figures, although the computations give some very crude approximation, the pressure fields are quite different. It also should be noted that, at the moment, the comparison is for one interaction, a rather strong one in our present framework. The computational results are also limited to the <u>initial</u> portion of the data presented in Ref. 1. The lack of ability to predict, in very good detail, the <u>original</u> single fin interactions is probably the major reason why the subsequent interaction is not very adequately simulated. It should also be noted that the "general" validation of the computation was made for quite strong shock waves (20^{o} at Mach number of 3), whereas, in the present complex geometries, the shock wave strengths are much smaller. There has been little in the way of computational validation for weak shock waves. It is important to stress the necessity of validating the computations for the weak waves used in the present studies <u>before</u> drawing any general conclusions about the capability of computation to reasonably predict the complicated structure which is developed. The use of computation, in their present form, to derive flow field structures downstream may be severely compromised in the light of their inability to reasonably predict the complicated surface pressure distribution patterns noted herein. Since the new experiments have shown that there is little effect of the exit conditions for the 9" fins of Ref. 1, the data set provides a full flow field to test the computation to a considerable degree.

b) The Reflected Shock Interaction, Fig. 8

The reflected shock interaction provides a unique test of the intersection of a three-dimensional and a two-dimensional interaction in a corner. Both of these interactions have been studied separately, and have been computed with varying degrees of success. The interaction of these two flowfields provides a unique test of flowfield modeling and computational validation. The first mean wall static pressure data which has been analyzed was presented in Ref. 5 at the January 1991 AIAA Meeting. The data set, which was completed under the subject grant, includes three different fin lengths and two positions of the fin with respect to the flat plate. Little of this data, beyond that presented at the AIAA Meeting, has been completely reduced, and no computations have been made to date.

Results and Discussion

1) In Fig. 9, the pressure contours on the wall and floor for 6^o, 8^o, and 11^o interactions are presented. There is a general similarity in the constant pressure contours. Starting from close to the wall centerline, there is a region of 1/2 to about 1 inch where the pressure contours are approximately normal to the initial flow. Then there is a fanning out, both upstream and downstream, as one approaches the corner. It is possible to pick out one pressure contour which looks almost two-dimensional over the entire span, but it is clear that the corner interaction has had a major effect on a large part of the "two-dimensional" flow. If one examines the "three-dimensional fin flowfield" starting with station -2.3, the effects on the three-dimensional fin flowfield is clearly seen.

2) Some general idea of the interaction of the two- and three-dimensional flows can be outlined by noting the change in the two- and three-dimensional characteristics. The dotted lines in Fig. 9 show the upstream boundary of this large interaction region, which will clearly dominate the flows downstream. Quite

contrary to expectations, the shape and extent of this "corner interaction" does not, from these first results, appear to differ significantly for different shock strengths. A comparison of the 6^{o} and the 11^{o} interaction shows a shift streamwise (due to a shift in the shock impingement point), but no substantial difference in the upstream boundary. The effect of the two-dimensional interaction, clearly unseparated for the 6^{o} shock and separated for the 11^{o} shock, does not appear to have a major effect on the resulting upstream surface pressure distribution influence. Further results for other angles (now under study) may clarify this trend, but flow field results are needed to critically evaluate this trend.

3) From the examples presented, it is quite clear that the flow in the corner is quite different and cannot be directly derived from the classical two-dimensional or three-dimensional flows. From the information presented, there is no way to derive the vortical structure which flows downstream. More detailed information, particularly flowfield details, will be required to determine the structure of the interaction and the downstream propagation of the complex vortical field generated in the corner.

a-b Comments

Future work on this complex interaction, as well as continuing work on the cross shock configuration mentioned earlier, must emphasize the requirements for flowfield information to determine flow structure. Of equal importance, although not obvious from the discussions presented herein, is the need for detailed surface information, both mean and non-steady pressures and heat transfer. Such data would provide a framework for a better understanding and prediction of such flows, and to provide a specific target for computation. The determination of the effects of the downstream boundary (exit conditions) requires, in this author's mind, comparable tests with different length fins, and flowfield details, to assure that

upstream propagation effects are not important in the data presented.

Both of the test set-ups for the crossing and reflected shock interactions were carried out in a model-wind tunnel configuration which permits optical access for applications of new laser techniques to probe the flow field. A survey rake for total pressure and static pressure near the exit of these configurations has also been completed, but has not been used. Preliminary tests of Reyleigh scattering techniques using UV lasers have shown that shock waves and boundary layers can be captured by a UV camera, and further development can provide key flow field information to supplement the detailed wall static pressure distributions obtained in the current program.

c) Boundary Layer Studies

Both the crossing and reflected shock configurations were enclosed between two sharp, flat plates which extended approximately 7 inches upstream of the fin leading edge. The enclosure provides a well-defined initial and boundary conditions for computations. However, whereas most of the original work on simple configurations took place using the wind tunnel wall boundary layer, which was quite thick and permitted detailed measurements, the flat plates used to enclose the cross shock and reflected shock provide much thinner layers which have not been totally defined for computation. To provide a calibration for the computations of the boundary layer before the interaction, detailed studies were initiated on a sharp flat plate, with surveys being made at three longitudinal locations and a series of transverse locations at each longitudinal station. Although the original concept was to obtain a full Reynolds number variation of length and stagnation pressure, during the subject period only the boundary layer on the flat plate with a stagnation pressure of 100 psia (the primary test condition) was obtained. The results for the three stations are presented in Ref. 5, and should be used as the first test of

computational capability <u>before</u> the detailed interaction within the configuration is carried out.

2. DEFERRED STUDIES

Over the past years, as the primary studies were being carried out, several key elements arose which became the subject of parallel research activities. These were all deferred during the subject period, but are key elements which should be considered in further research in this area.

a) The present test configuration was deliberately set up to have symmetry around a horizontal plane, i.e. the top and bottom boundary layer conditions were the same. For symmetrical shock crossing interactions, this provided two planes of symmetry simplifying the computational problem. One key element of the crossing shock interaction program was to consider the phenomena when the boundary layers on the top and bottom walls are different. This is a specific case for many of the high speed inlets considered in the inlet-airframe integration problem. The original plans were to carry out the crossing shock interaction with one plate and with the fins extending to the tunnel wall, to provide a test of this problem.

b) Since the interaction is a shock wave boundary layer one, the effects of Reynolds number on the boundary layer characteristics and the performance of simple and complex interactions under Reynolds number variations should be carried out. Both the symmetrical cases and the asymmetric cases noted in a) above, as well as several simple configurations should be examined.

c) Many of the basic studies have been extended, in recent years, to rather strong shocks to permit better definition of the flowfield structure. However, for many interactions of practical interest, the shocks will be weak. Much of the effort on "strong" shocks, approximate conical flows, separation (however it is defined), and flow field details may not be appropriate for the weak shocks in inlets and in external aerodynamics of practical bodies. Some attempt has been made in the complex interactions, noted previously, to extend the tests to

interactions which have not been examined for shock strengths of this low a value in the basic studies. Such basic studies should be undertaken, since the "conical" approximation and proposed flow structures may not be appropriate.

d) The results for both the basic and early cross shock work have indicated, through high frequency wall static pressure measurements, that the flow is unsteady, to some degree. All of this work was deferred during the current years because of the complexity and time constraints for such tests. However, they provide a key element of input into concepts for turbulence modeling for computations for such studies. They may be an important element in the computation and the use of the results for downstream conditions.

e) It has become clear over the past several years that the measurement of heat transfer on the wall, in considerable detail and at high frequency, would provide a new and very important element for future applications and computational validation. Although under the subject contract, a concept was developed, and an early version of a gauge was constructed, this work has been deferred. It should be a key item for future activities.

f) There has been a continuous question of validity of test data when there is essentially no duplication of the results available from the Gas Dynamics Laboratory 8" x 8" High Reynolds Number Supersonic Tunnel. One of the major thrusts of the program of some years ago included the construction of a Low Turbulence Variable Geometry Tunnel which, when operational, could provide the first direct comparison for a complex or simple interaction in two tunnels at the same Reynolds number and Mach number, but with different turbulence fields. This would provide an important impact for future studies.

g) An examination of the complex interactions which have been studied in the last two years has shown that the definition of the flowfield downstream of the

primary interaction is of key importance in building the structure for the following flowfield. The Low Turbulence Variable Geometry facility was designed to study the flow downstream of simple interactions, but the tunnel was never brought into operation and all work has been deferred.

3. COMMENTS ON THE FUTURE

The details of the previous two sections defines a framework for a long term program on shock wave turbulent boundary layer interactions. The support of OSR and NASA for the past years has provided a unique base for future activities and included the initiation of the programs carried out at Penn State and the University of Texas, Austin. In addition, these activities have spurred complementary and parallel studies in Europe. However, the link between the major advances which have been made in the basic studies to applications to real vehicles has not been strong. The complex interactions which have been the emphasis of the present studies over the past years is an attempt to help bridge that gap. An understanding of the applied problems for external, internal, and inlet-airframe integration can provide some guidance for future studies. The inclusion of heat transfer is particularly important for extensions to higher Mach numbers.

4. REPORTS AND PUBLICATIONS

The first phase results on the cross shock configuration were presented during the previous year, Ref. 1. The unsteady studies and the first results of the reflected shock are presented in Refs. 2, 3 and 5. Analysis of the crossing shock results, carried out without support of the present grant, were presented at the January 1992 AIAA Meeting, Ref. 4. Further reports and publications, using the generated data base, will depend on time and funding availability. The work of Ref. 6, although completed under previous support, was presented during this grant period.

REFERENCES - REPORTS PUBLISHED

1) Batcho, P. F., Ketchum, A. C., Bogdonoff, S. M. and Fernando, E. M., "Preliminary Study of the Interactions Caused by Crossing Shock Waves and a Turbulent Boundary Layer," AIAA Paper #89-0359, January 1989.

2) Poddar, K. and Bogdonoff, S. M., "A Study of Unsteady Crossing Shock Turbulent Boundary Layer Interactions," AIAA Paper #90-1456, June 1990.

3) Narayanswami, N., Knight, D., Bogdonoff, S. M. and Horstman, C. C., "Crossing Shock Wave-Turbulent Boundary Layer Interactions," AIAA Paper #91-0649, January 1991.

4) Bogdonoff, S. M. and Stokes, W. L., "Crossing Shock Wave Turbulent Boundary Layer Interactions - Variable Angle and Shock Generator Length Geometry Effects at Mach 3," Abstract submitted for consideration of paper to be presented at the AIAA 30th Aerospace Sciences Meeting, Reno, Nevada, January 1992.

5) Bogdonoff, S. M. and Poddar, K., "An Exploratory Study of a Three-Dimensional Shock Wave Turbulent Boundary Layer Interaction in a Corner," AIAA Paper #91-0525, January 1991.

6) Toby, A. Steven and Bogdonoff, S. M., "An Exploratory Study of Corner Bleed on a Fin Generated Three-Dimensional Shock Wave Turbulent Boundary Layer Interaction," AIAA Paper #89-0356, January 1989.

5. THIRD YEAR PROGRAM

Introduction

The current section summarizes the major results obtained under the sponsorship of AFOSR Grant 89-0033, monitored by Dr. L. Sakell, for the period October 1, 1990 to August 31, 1991. During this period, the funding was only sufficient to support the tuition and stipend of a single graduate student Wolfgang Konrad, and this section will summarize his progress.

For the past several years, considerable experimental work at the Princeton Gasdynamics Laboratory has been directed towards a better understanding of turbulent shear layer behavior at Mach 3. A wide variety of flow configurations has been studied, including high Reynolds number, zero pressure gradient flat plate boundary layers (Spina and Smits 1987, Spina et al. 1991, Smith and Smits 1991), flat plate boundary layers with adverse and favorable pressure gradients (Fernando and Smits 1989, Smith and Smits 1992), boundary layers on concavely curved walls (Jayaram et al. 1987, Donovan et al. 1991), shock wave boundary layer interactions (Smits and Muck 1987, Selig et al. 1989), and flow over a backward-facing step (Hayakawa et al. 1985, Shen et al. 1990).

With support from Grant 89-0033, Wolfgang Konrad started a new investigation: the detailed study of a three-dimensional turbulent boundary layer at Mach 2.87. The three-dimensionality is introduced by a curved sharp fin, designed to produce a swept isentropic compression (see Figure 1 in AIAA Paper 92-0310, attached). The maximum flow deflection in the freestream is 20^{o}, corresponding to a pressure rise of a factor of about three. The aims of the research are: (1) to study the response of compressible turbulence to the onset of three-dimensionality; (2) to determine the accuracy of a computational method (the method used by Professor Knight of Rutgers University) to compute the flow; (3) to develop recommendations for

turbulence modeling in compressible three-dimensional flow (for example, the use of non-isotropic eddy viscosities); (4) by comparison with similar two-dimensional pressure gradient flows, to assess the effect of in-plane curvature as a possible mechanism for turbulence suppression; and (5) to determine the usefulness of such isentropic or "soft" compressions in application to inlet design as a means of reducing flow losses associated with shocks and improving the compressor entry flow.

Experiment and Experimental Results

The experimental details and preliminary results were presented at the 30th Aerospace Sciences Meeting in Reno, Nevada, January 6-9, 1992. The paper, number 92-0310 entitled "A Three-Dimensional Supersonic Turbulent Boundary Layer Generated by an Isentropic Compression", authored by W. Konrad, A.J. Smits and D. Knight, is attached to this report. The paper also gives a first comparison between the experiment and the computation by Knight. The results show that the simple Baldwin-Lomax model used in the computation captured the overall flowfield quite well. Generally, however, there was a tendency to underpredict the upstream extent of the interaction, and to overestimate the degree of turning experienced by the boundary layer flow. (See AIAA Paper 92-0310, attached, for further details).

Future Work

To document the turbulence structure, the primary tool will be the hot-wire anemometer, which gives velocity information at one or more points in the flow. Extensive measurements of wall pressure fluctuations will be made using miniature, high-frequency-response pressure transducers, and we hope to measure surface heat transfer fluctuations using thin-film gauges. During the last two years, we have also implemented Rayleigh scattering to obtain instantaneous density distributions in a plane, and we are just starting to use Raman Excitation and Laser-Induced

Fluorescence (RELIEF) to acquire velocity data along a line.

We plan to use these techniques to provide information on the structure of the turbulence in the three-dimensional flow, and some early results on space correlations of the density field using Rayleigh scattering have already been obtained (see Figure 10).

References

Hayakawa, K., Smits, A.J. and Bogdonoff, S.M., "Turbulence Measurements in a Compressible Reattaching Shear Layer", AIAA Journal, Vol.22, pp.889-895, 1984.

Jayaram, M., Taylor, M.W., and Smits, A.J., "The Response of a Compressible Turbulent Boundary Layer to Short Regions of Concave Surface Curvature", Journal of Fluid Mechanics, Vol.175, pp.343-362, 1987.

Spina, E.F. and Smits, A.J., "Organized Structures in a Compressible Turbulent Boundary Layer", Journal of Fluid Mechanics, Vol.182, pp.85-109, 1987.

Smits, A.J. and Muck, K.C., "Experimental Study of Three Shock Wave Turbulent Boundary-Layer Interactions", Journal of Fluid Mechanics, Vol.182, pp.291-314, 1987.

Selig, M.S., Andreopoulos, J., Muck, K.C., J.P. Dussauge and Smits, A.J., "Turbulence Structure in a Shock-Wave/Turbulent Boundary Layer Interaction", AIAA Journal, Vol.27, pp.862-869, 1989.

Fernando, E.M. and Smits, A.J., "A Supersonic Turbulent Boundary Layer in an Adverse Pressure Gradient," Journal of Fluid Mechanics, Vol.211, pp.285-307, 1990.

Spina, E.F., Donovan, J.F. and Smits, A.J., "On the Structure of High-Reynolds-Number Supersonic Turbulent Boundary Layers," Journal of Fluid Mechanics, Vol. 222, pp.293-327, 1991.

Donovan, J.F., Spina, E.F. and Smits, A.J., "The Structure of Supersonic Turbulent Boundary Layers Subjected to Concave Surface Curvature." Submitted Journal of Fluid Mechanics, 1991.

Smith, D.R. and Smits, A.J., "The Rapid Expansion of a Turbulent Boundary Layer in a Supersonic Flow," to appear Journal of Theoretical and Computational Fluid Dynamics, 1991.

Shen, Z.H., Smith D.R. and Smits, A.J., "Wall Pressure Fluctuations in the Reattachment Region of a Supersonic Free Shear Layer", AIAA Paper #90-1461, AIAA 21st Fluid and Plasmadynamics Conference, Seattle, Washington, June 18-20 1990. Submitted for publication Experiments in Fluids.

Konrad, W., Smits, A.J. and Knight, D., "A Three-Dimensional Supersonic Turbulent Boundary Layer Generated by an Isentropic Compression." Submitted for presentation, AIAA 30th Aerospace Sciences Meeting, Reno, Nevada, January 1992.

Smith, D.R. and Smits, A.J., "The Effect of Multiple Distortions on the Boundary Layer in a Supersonic Flow." Submitted for presentation, AIAA 30th Aerospace Sciences Meeting, Reno, Nevada, January 1992.

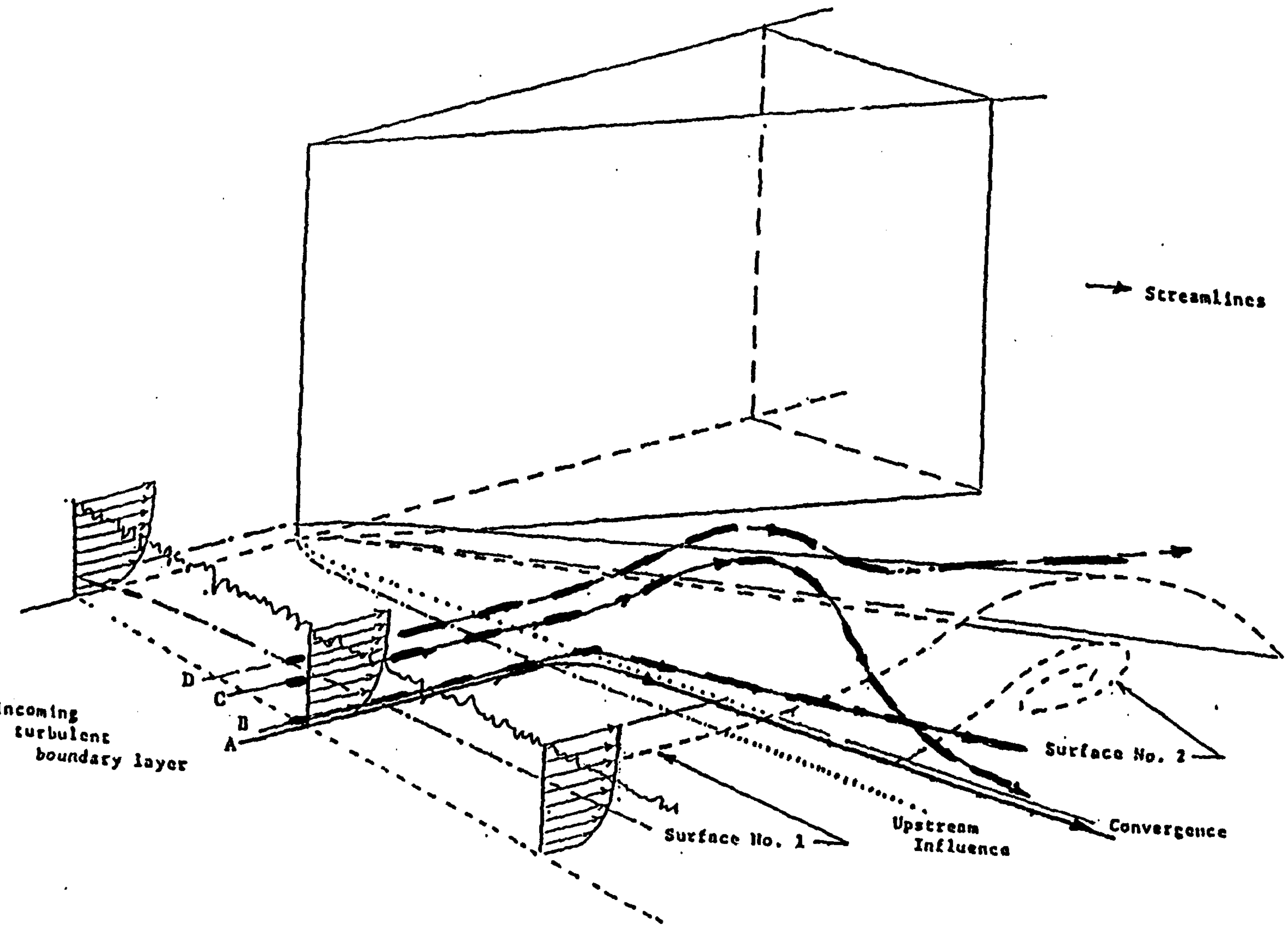


Fig. 1. Fin Flow Field Structure (not to scale).

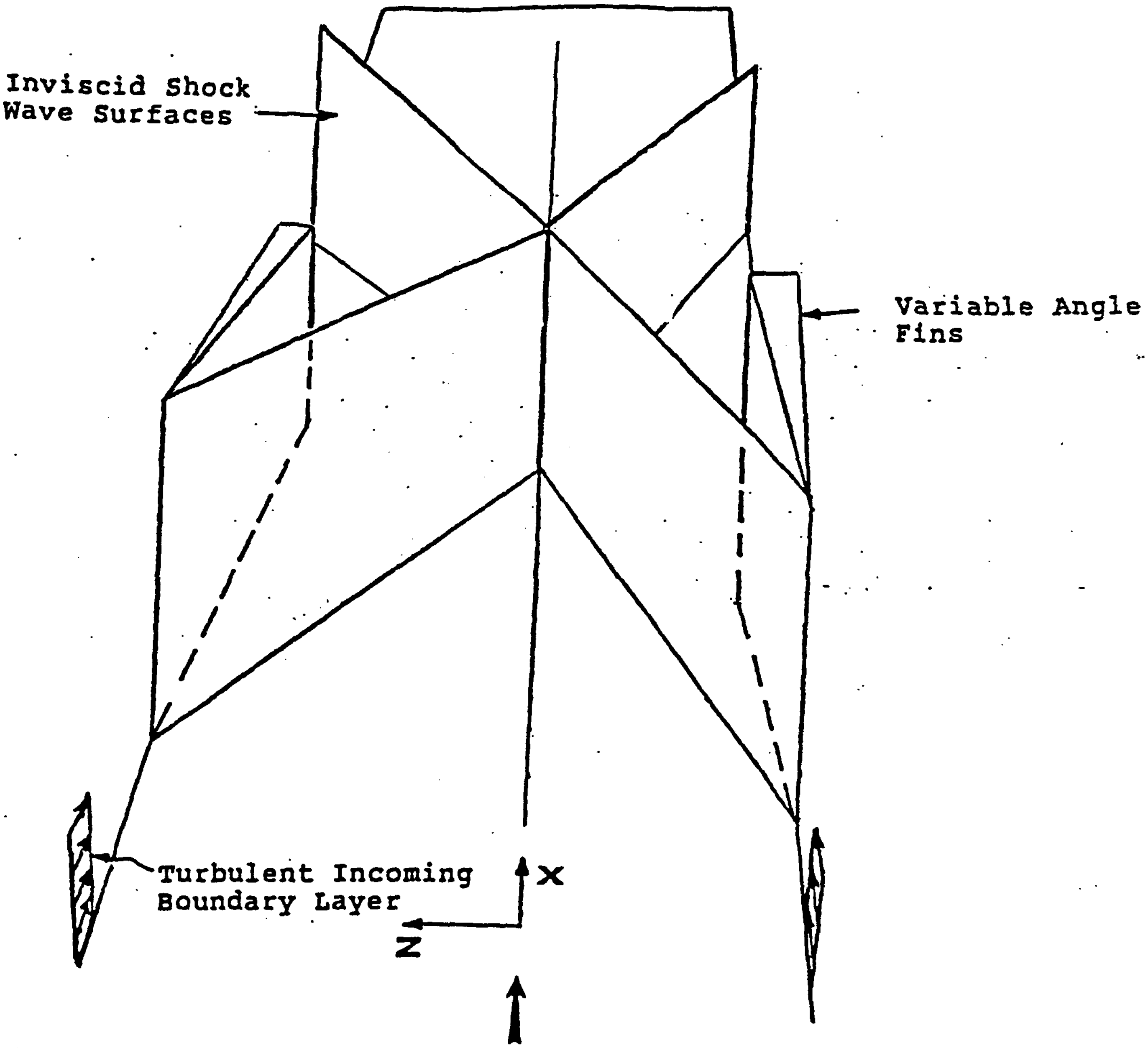
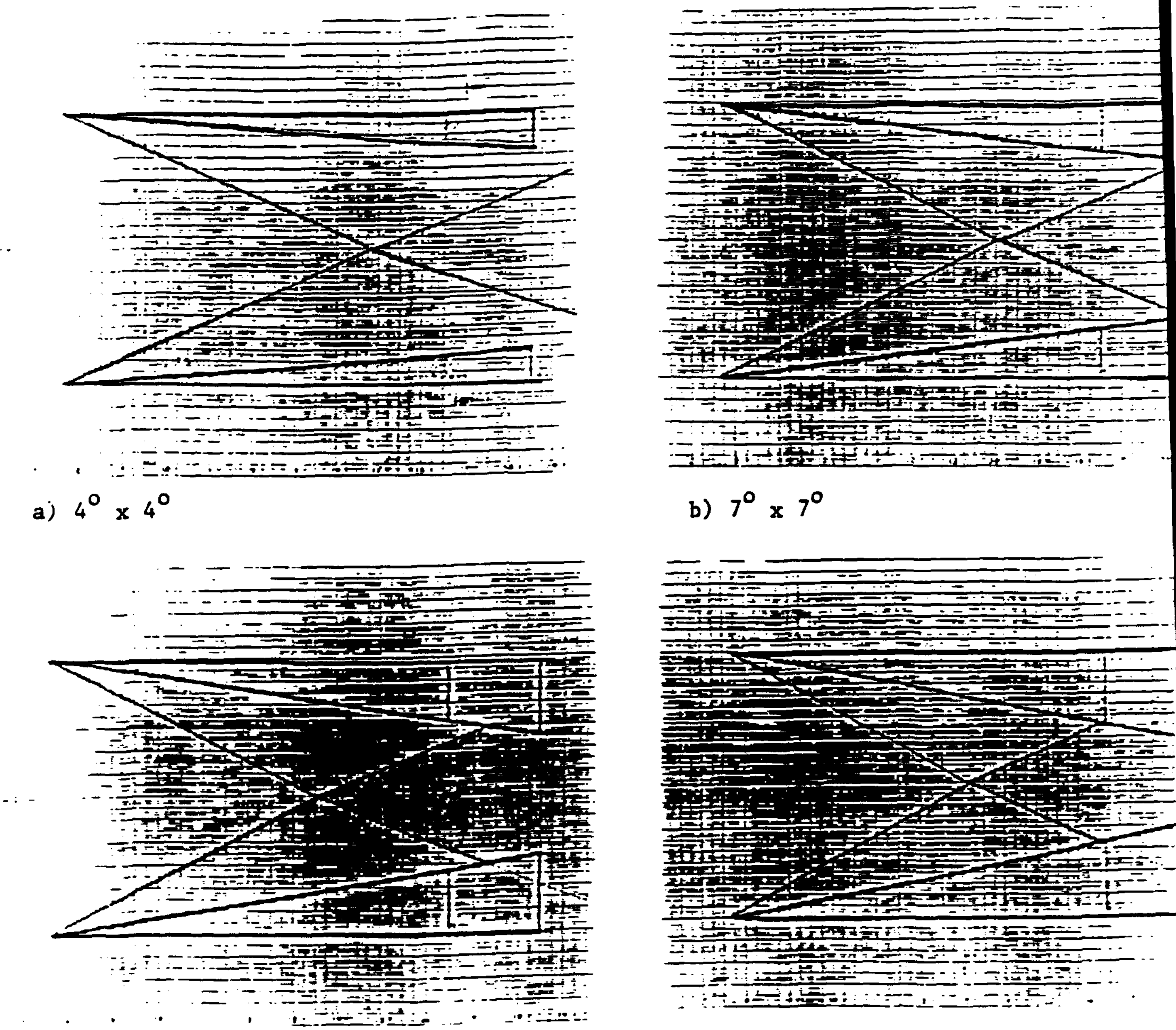


Fig. 2. Geometry of the X-shock wave turbulent boundary layer interaction study. Top and bottom plates extending approximately seven inches upstream of the fins enclose the four inch high fins separated by six inches at the tips.



a) $4^{\circ} \times 4^{\circ}$

b) $7^{\circ} \times 7^{\circ}$

c) $9^{\circ} \times 9^{\circ}$

d) $11^{\circ} \times 11^{\circ}$

Fig. 3. Sketch of inviscid shock waves in several crossing shock symmetrical configurations.

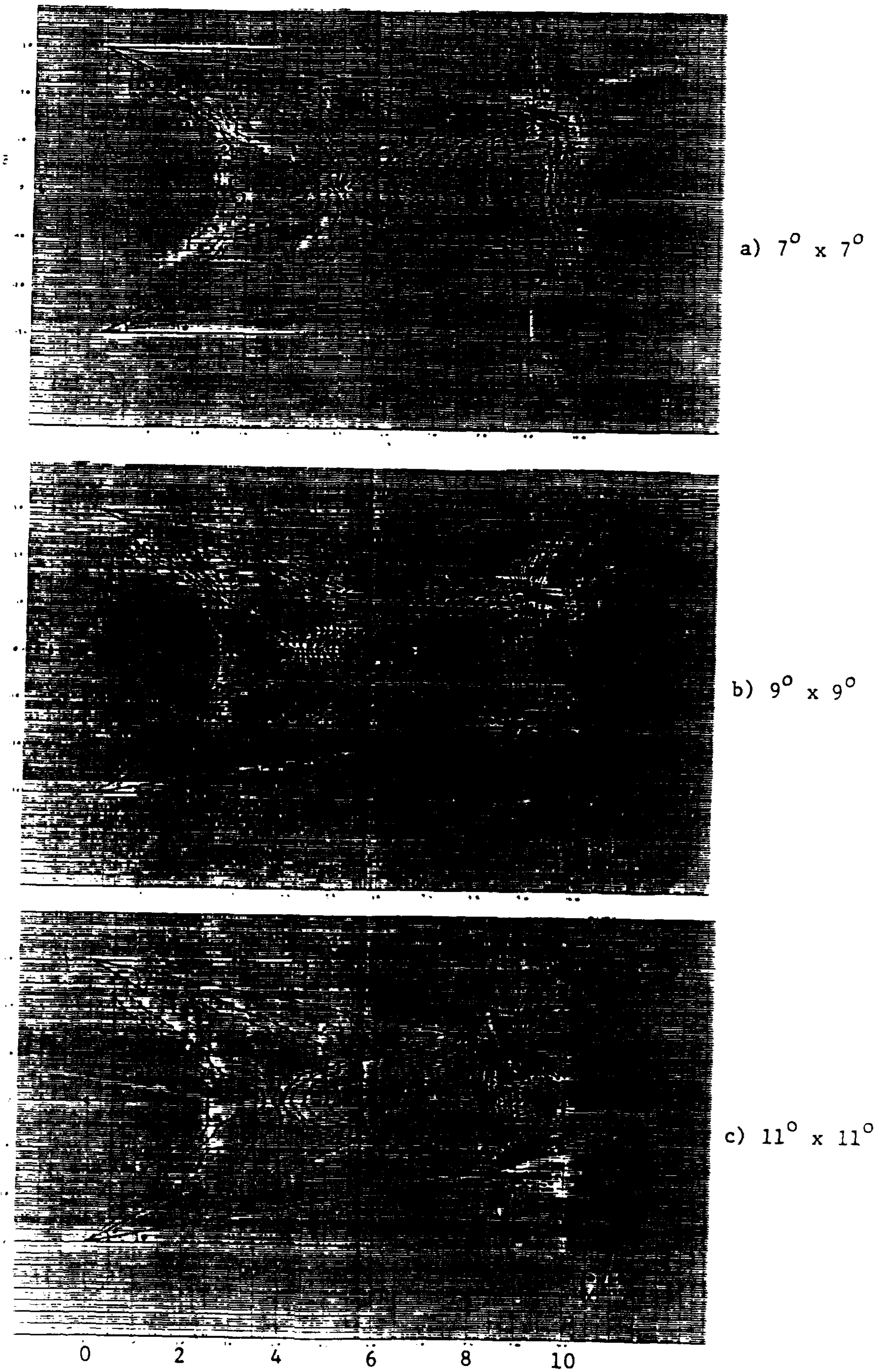
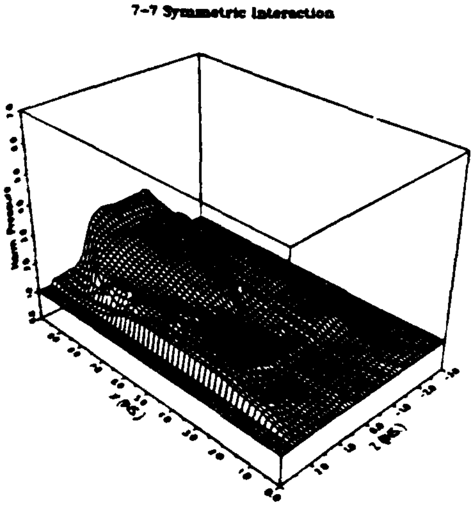
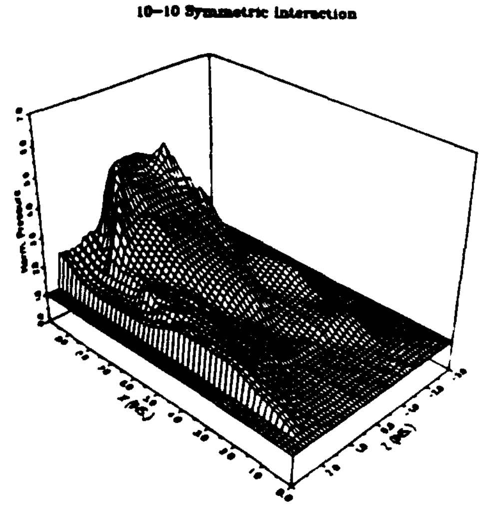
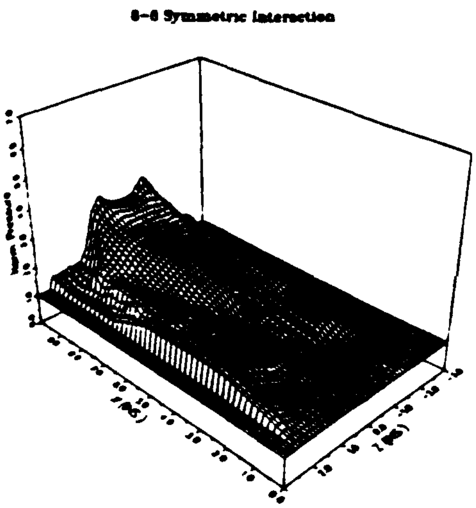
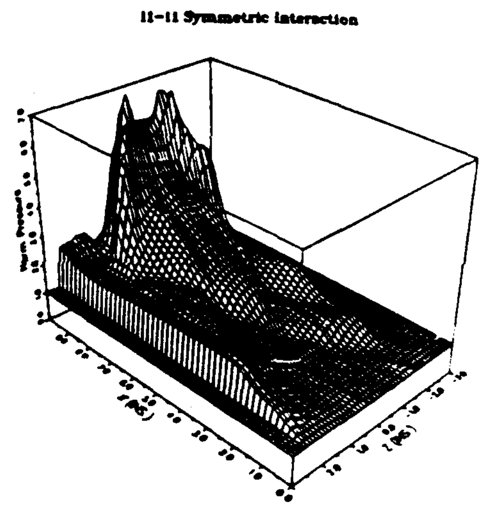


Fig. 4. Examples of detailed wall static distributions for three X-shock symmetrical configurations. 9" long fins, M = 2.93.









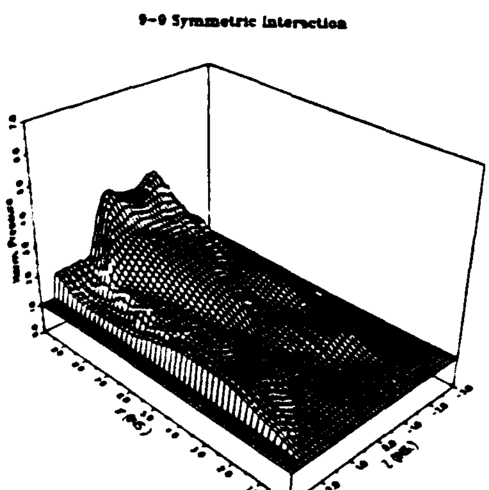


Fig. 5. Example wall static pressure carpet plots for 9" long fins, X-shock symmetrical configurations, $M = 2.93$, 7° to 11° fin deflections.

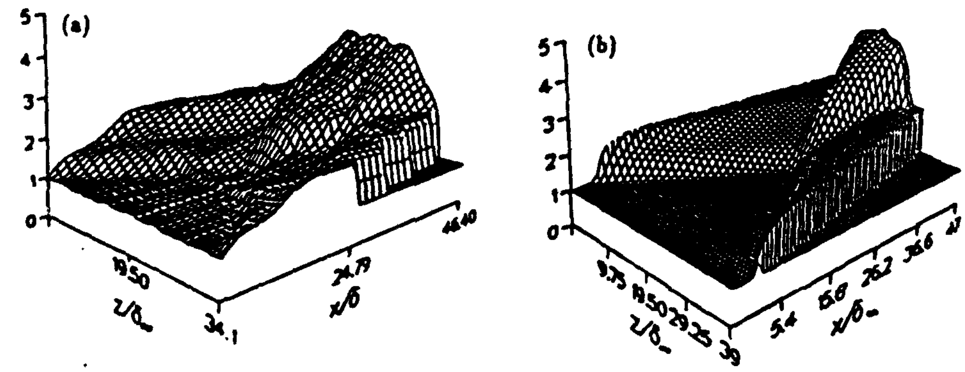


Fig. 6 . Static pressure (P/P_∞) (a) Experiment, (b) Computation $11^\circ \times 11^\circ$ interaction. From Ref. 3 .

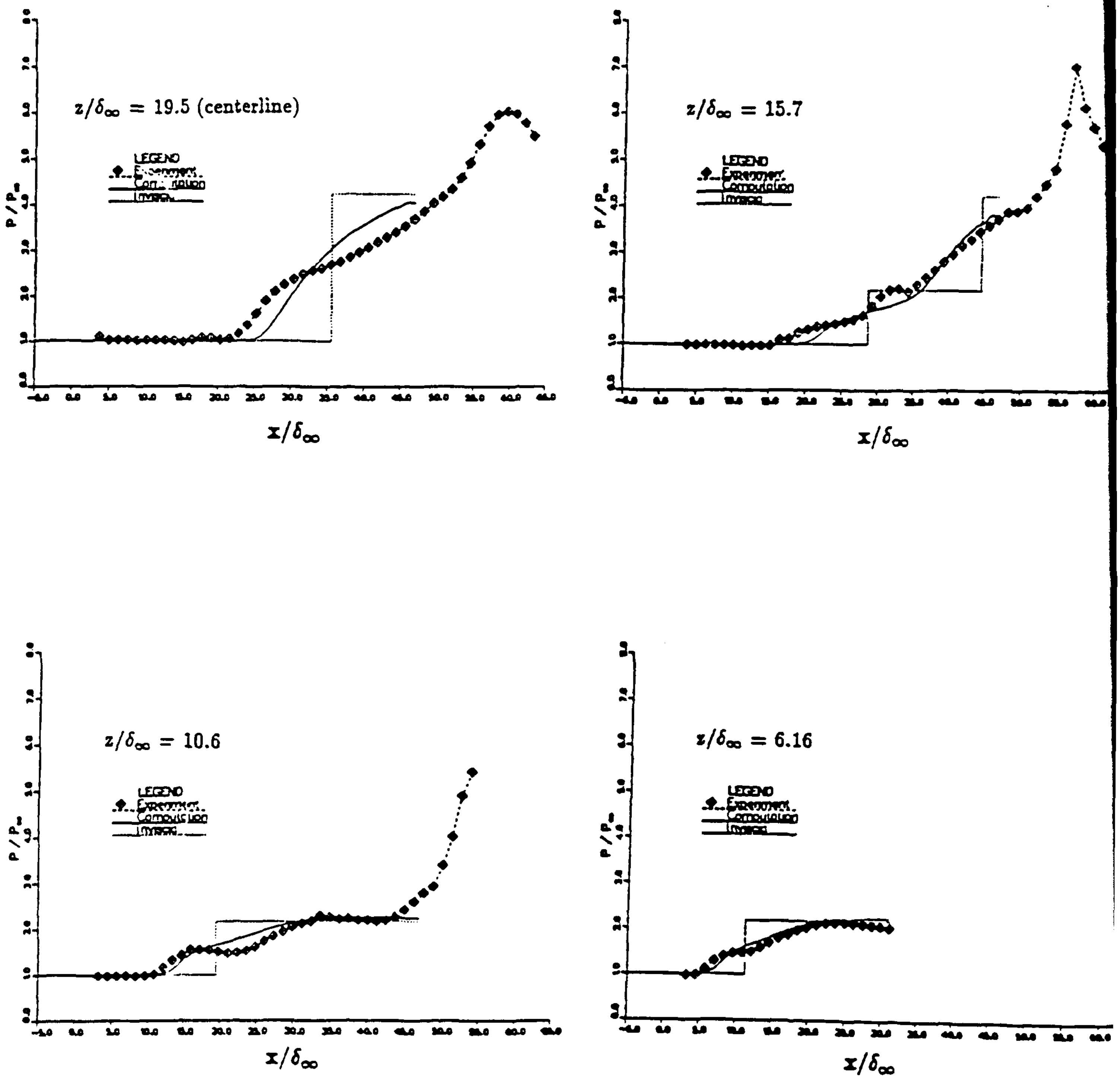


Fig. 7. **Experimental and Computed Pressure on Streamwise cuts $11^0 \times 11^0$ interaction** (from Ref. 3).

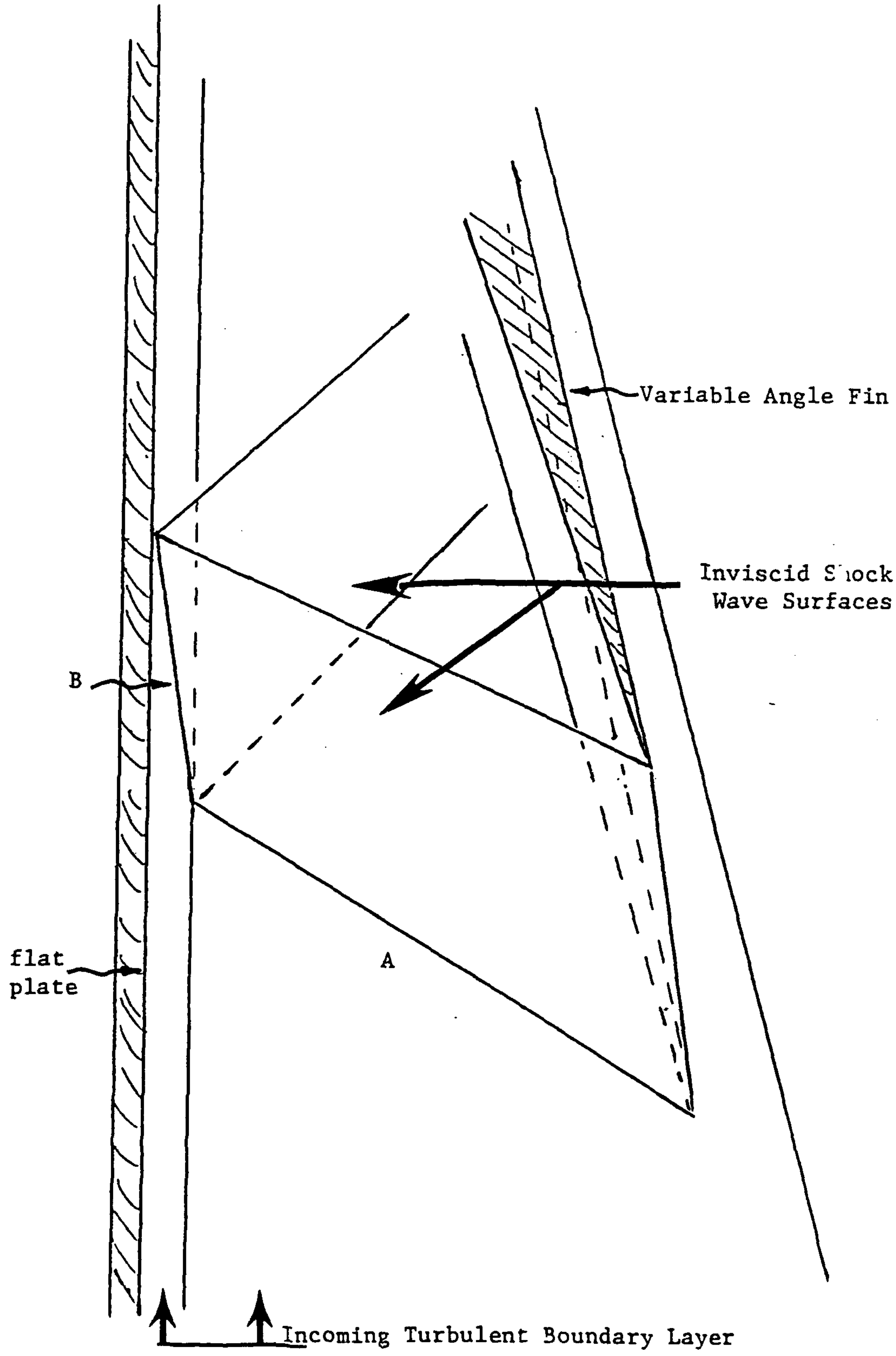


Figure 8. Fin Shock Wave Reflecting Geometry (Corner Flow).

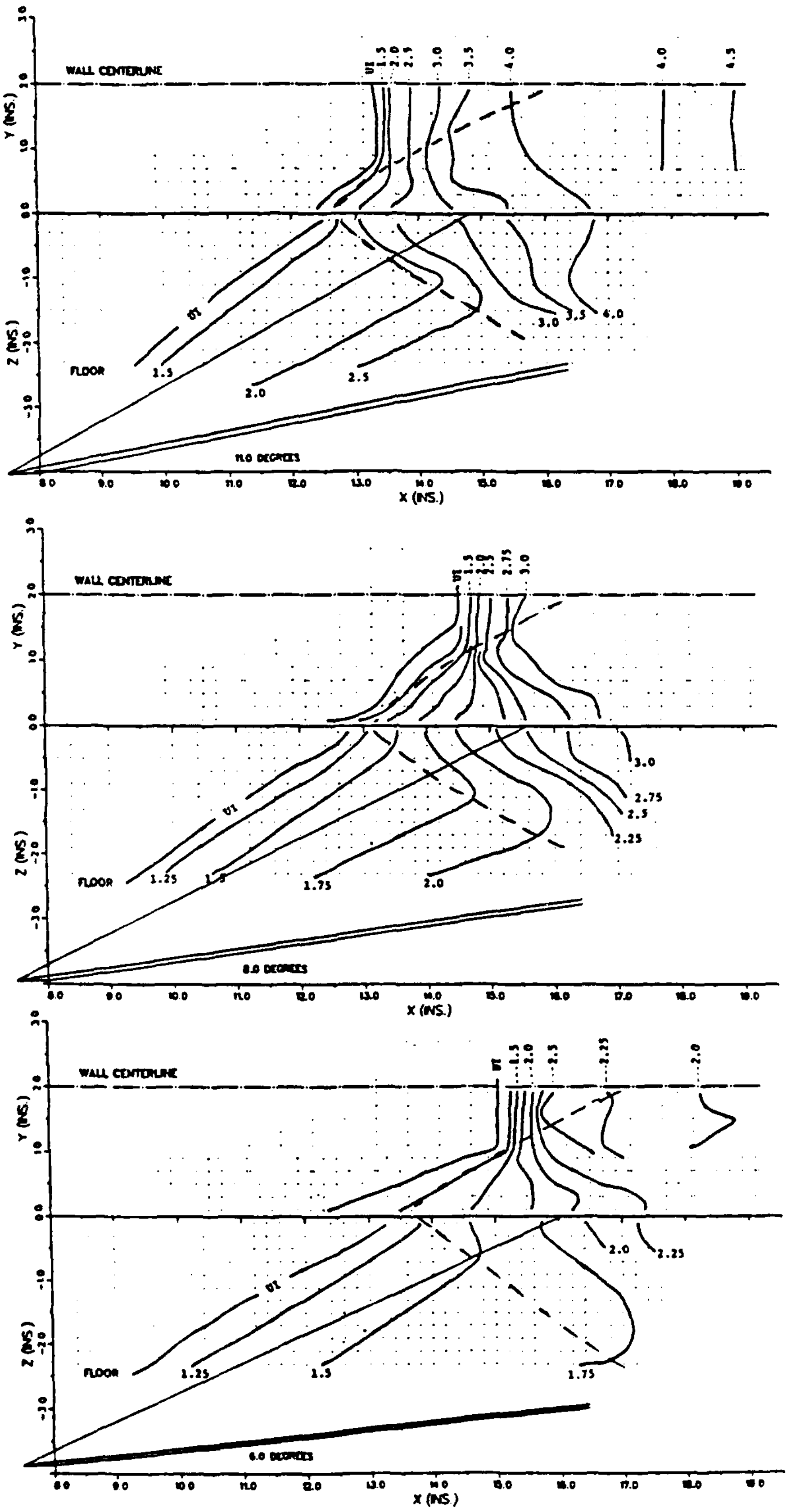
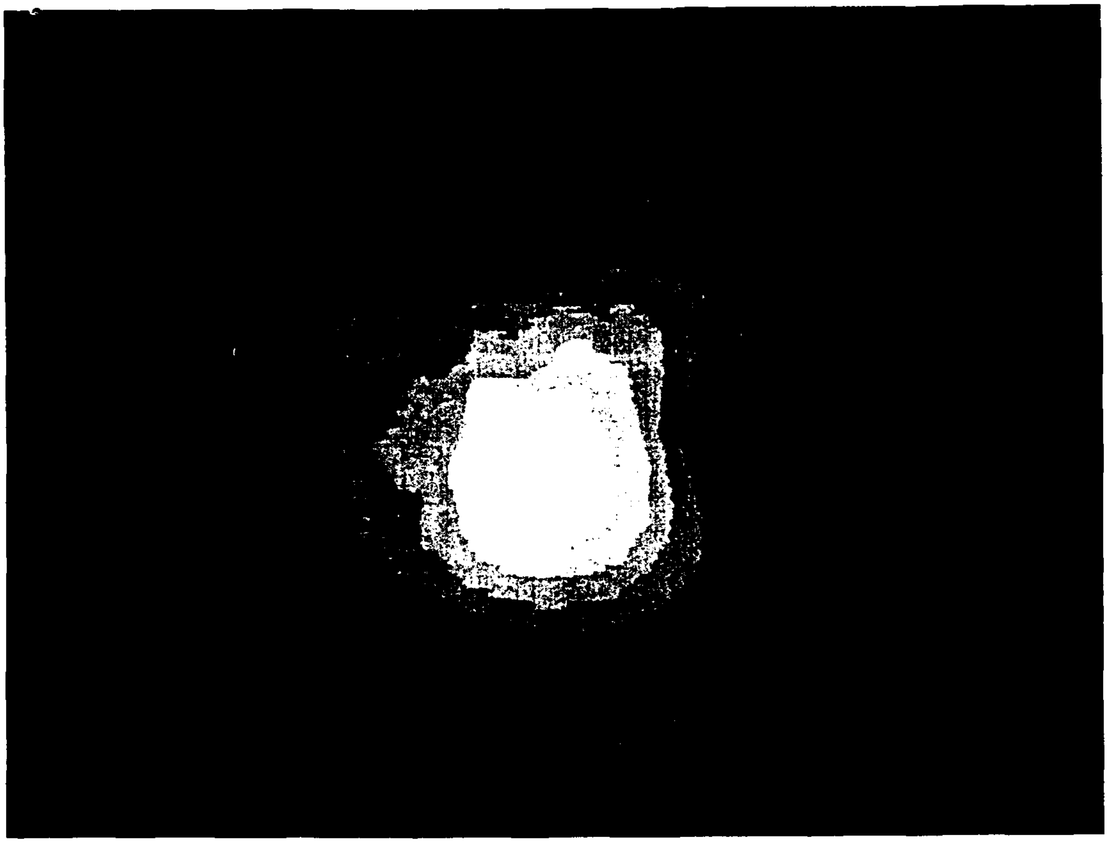
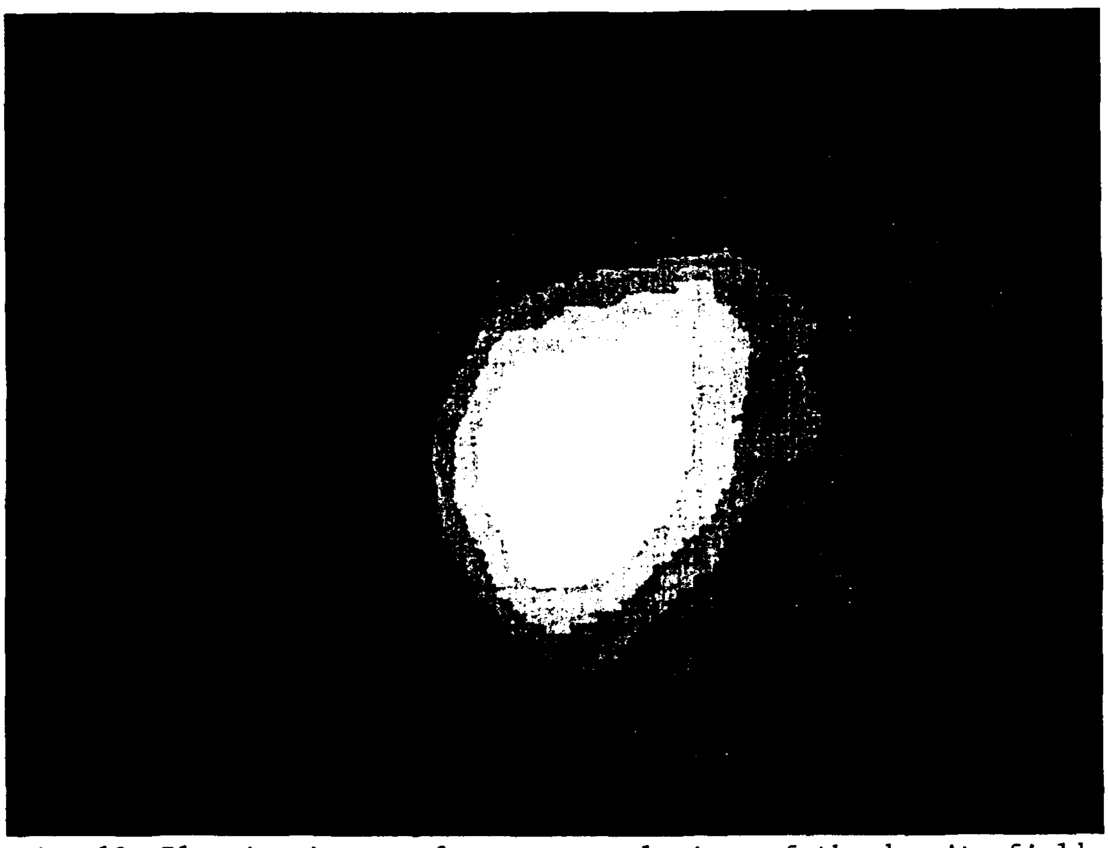


Fig. 9 . Mean Pressure Contours on the Floor and Wall for Several Fin Angles, 6°, 8°, and 11°, Approximate Upstream Boundary of 3-D/2-D Interaction.



a)



b)

Fig. 10. Planview images of space correlations of the density field obtained by averaging 160 Rayleigh scattering images. (a) Undisturbed Mach 2.9 boundary layer flow. Flow is from left to right. (b) Three-dimensional boundary layer at the second survey point shown in Fig. 7 of AIAA Paper 92-0310, attached. The wall distance is the same in both images, that is, 0.6 times the boundary layer thickness.